INVESTIGATION 7-A

The Nature of the Electrostatic Force

TARGET SKILLS
- Hypothesizing
- Performing and recording
- Analyzing and interpreting

In this investigation, you will use pith balls to quantitatively analyze the electrostatic force of repulsion.

Problem

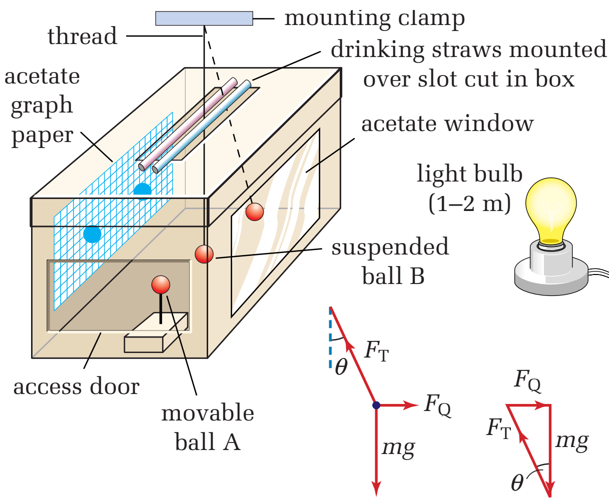
What is the relationship between electrostatic force and the distance of separation between two charged pith balls?

Equipment

- electronic balance
- clear straight filament lamp
- razor knife
- pith ball on thread
- pith ball mounted on wooden base
- acetate graph paper
- clear acetate sheet
- ebonite and fur
- cardboard shoe box
- two drinking straws

Procedure

CAUTION Be careful when using any sharp cutting object.



1. Cut rectangular holes in the front, rear, and side of the box and a slit on top, as shown.
2. Mount the clear acetate in the front hole and the acetate graph sheet in the rear. Mount the drinking straws on either side of the slit on top.
3. Poke the free end of the thread attached to pith ball B up between the drinking straws and mount on a clamp above. Ensure that the thread hangs vertically.
4. Place the pith ball with the wooden base (A) inside the box. Record the rest positions of both pith balls on the acetate grid.
5. Rub the ebonite with fur and reach in and charge both pith balls. Adjust the height of the mount of pith ball B so that it is level with pith ball A. Record the position of both pith balls.
6. Move pith ball A toward pith ball B several times. Adjust the mount of pith ball B each time to keep B level with A. For each trial, read and record the positions of both pith balls.
7. Measure the mass of a large number of balls and take an average to find the mass of one.

Analyze and Conclude

1. For each trial, use the rest positions and the final positions of the pith balls to determine the distance between A and B.
2. For each trial, use the lateral displacement of B, relative to its original rest position, to determine the electrostatic force acting on B. (Prove for yourself that $F_Q = mg \tan \theta$.)
3. Draw a graph with the electrostatic force on the vertical axis and the distance of separation between the charges on the horizontal axis. What does your graph suggest about the relationship between the electrostatic force and the distance of separation?
4. Calculate $1/r^2$ for each of your trials and plot a new graph of F versus $1/r^2$. Does your new graph provide evidence to back up the prediction you made in your original analysis? Discuss.

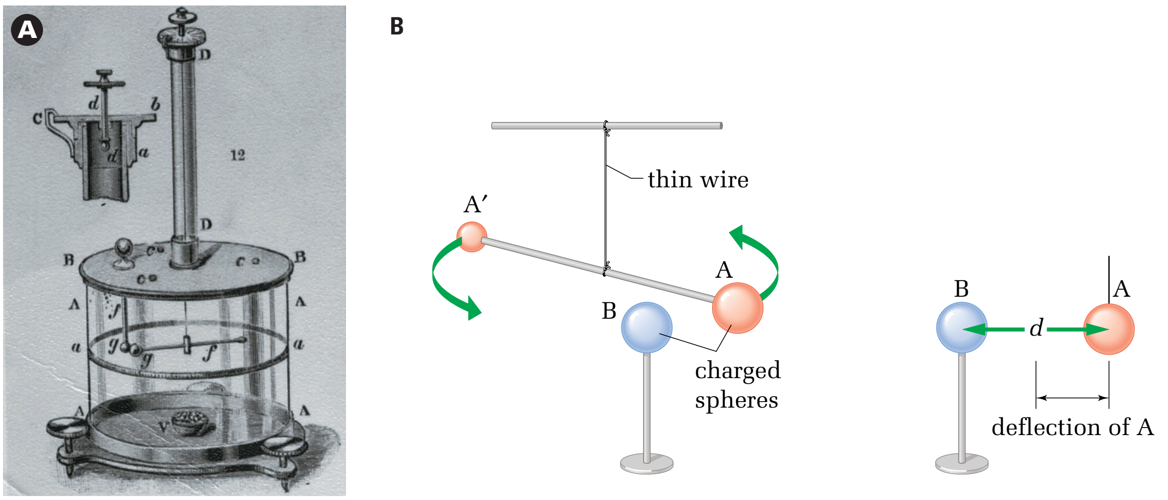
Electromagnetic Force

The exact nature of frictional forces and applied forces that are due to the electromagnetic force is very complex. How would anyone obtain fundamental information about such complex forces? Physicists start with the simplest cases of such forces, analyze these cases, and then extend them to more and more complex situations. The simplest case of an electromagnetic force is the electrostatic force between two stationary point charges.

Several scientists, including Daniel Bernoulli, Joseph Priestly, and Henry Cavendish, had proposed that the **electrostatic force** obeyed an inverse square relationship, based on a comparison with Newton's inverse square law of universal gravitation.

Coulomb's Experiment

French scientist Charles Augustin Coulomb (1736–1806) carried out experiments in 1785 similar to the investigation that you have just completed. Coulomb had previously developed a **torsion balance** for measuring the twisting forces in metal wires. He used a similar apparatus, shown in Figure 7.3, to analyze the forces between two charged pith balls.



Coulomb charged the two pith balls equally, placed them at precisely measured distances apart. Observing the angle of deflection, he was able to determine the force acting between them for each distance of separation. He found that the electric force, F, varied inversely with the square of the distance between the centres of the pith balls $\left(F_{\mathrm{Q}} \propto \dfrac{1}{r^2}\right)$.

To investigate the dependence of the force on the magnitude of the charge on the pith balls, Coulomb began with two identically charged pith balls and measured the force between them. He then touched a pith ball with a third identical but uncharged pith ball to reduce the amount of charge on the ball by half. He found that

Figure 7.3 Coulomb's torsion balance **(A)** is simplified in **(B)**. Coulomb measured the force required to twist the thread a given angle. He then used this value to determine the force between the two pith balls.

PHYSICS FILE

You can develop a sense of the meaning of the Coulomb constant by considering two charges that are carrying exactly one unit of charge, a coulomb, and located one metre apart. Substituting ones into Coulomb's law, you would discover that these two charges exert a force of 9.00×10^9 N on each other. This amount of force could lift about 50 000 railroad cars or 2 million elephants. Clearly, one coulomb is an exceedingly large amount of charge. Typical laboratory charges would be much smaller — in the order of μC or millionths of a coulomb.

the force was now only one half the previous value. After several similar modifications of the charges, Coulomb concluded that the electric force varied directly with the magnitude of the charge on each pith ball ($F_Q \propto q_1 q_2$). The two proportion statements can be combined as one $\left(F_Q \propto \frac{q_1 q_2}{r^2}\right)$ and expressed fully as **Coulomb's law**.

Any proportionality can be written as an equality by including a proportionality constant. Although the value of the constant was not known until long after Coulomb's law was accepted, it is now known to be $8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2}$, in SI units.

The value of the proportionality constant in a vacuum is denoted k and known as the **Coulomb constant**. In fact, air is so close to "free space" — the early expression for a vacuum — that any effect on the value of the constant is beyond the number of significant digits that you will be using. For practical purposes, the Coulomb constant is often rounded to $9.00 \times 10^9\ \mathrm{N \cdot m^2/C^2}$.

Coulomb's law can now be written as $F_Q = k\frac{q_1 q_2}{r^2}$. The direction of the force is always along the line between the two point charges. Between charges of like sign, the force is repulsive; between charges of unlike sign, the force is attractive.

COULOMB'S LAW

The electrostatic force between two point charges, q_1 and q_2, distance r apart, is directly proportional to the magnitudes of the charges and inversely proportional to the square of the distance between their centres.

$$F_Q = k\frac{q_1 q_2}{r^2}$$

Quantity	Symbol	SI unit
electrostatic force between charges	F_Q	N (newtons)
Coulomb's constant	k	$\frac{\mathrm{N \cdot m^2}}{\mathrm{C^2}}$ (newton · metres squared per coulomb squared)
electric charge on object 1	q_1	C (coulombs)
electric charge on object 2	q_2	C (coulombs)
distance between object centres	r	m (metres)

Unit Analysis

$$\text{newton} = \frac{(\text{newton})(\text{metre})^2}{(\text{coulomb})^2} \cdot \frac{(\text{coulomb})(\text{coulomb})}{(\text{metre})^2}$$

$$\frac{\mathrm{N} \cdot \cancel{\mathrm{m}^2}}{\cancel{\mathrm{C}^2}} \cdot \frac{\cancel{\mathrm{C}} \cdot \cancel{\mathrm{C}}}{\cancel{\mathrm{m}^2}} = \mathrm{N}$$

PHYSICS FILE

Note that not only does the proportionality constant have to validate the numerical relationship, it must also make the units match. Thus, the units for k are obtained by rearranging the Coulomb equation.

$$k = \frac{F \cdot d^2}{q_1 \cdot q_2} = \frac{(\text{force})(\text{distance})^2}{(\text{charge})(\text{charge})} = \frac{\mathrm{N \cdot m^2}}{\mathrm{C^2}}$$

Strictly speaking, the description of Coulomb's law given on the previous page is meant to apply to point charges. However, just as Newton was able to develop the mathematics (calculus) that proved that the mass of any spherical object can be considered to be concentrated at a point at the centre of the sphere for all locations outside the sphere, so it might also be proven that if charge is uniformly distributed over the surface of a sphere, then the value of the charge can be considered to be acting at the centre for all locations outside the sphere.

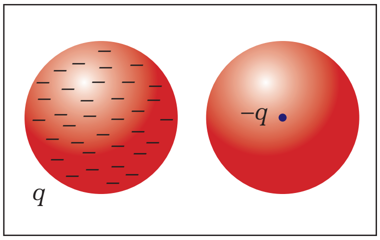


Figure 7.4 A uniformly charged sphere acts as if all of its charge is concentrated at its centre.

SAMPLE PROBLEM

Applying Coulomb's Law

A small sphere, carrying a charge of –8.0 μC, exerts an attractive force of 0.50 N on another sphere carrying a charge with a magnitude of 5.0 μC.

(a) What is the sign of the second charge?

(b) What is the distance of separation of the centres of the spheres?

Conceptualize the Problem

- *Charged spheres* appear to be the same as *point charges* relative to any point *outside* of the sphere.
- The *force*, *charge*, and *distance* are related by *Coulomb's law*.

Identify the Goal

The sign, ±, and separation distance, r, of the charges

Identify the Variables and Constants

Known		Implied	Unknown
$q_1 = -8.0 \times 10^{-6}$ C	$F = 0.50$ N	$k = 9.0 \times 10^9 \dfrac{\text{N}\cdot\text{m}^2}{\text{C}^2}$	r
$\lvert q_2\rvert = 5.0 \times 10^{-6}$ C			

Develop a Strategy

Since the spheres are uniformly charged, they can be considered to be points and Coulomb's law can be applied.

$$F = k\frac{q_1q_2}{r^2}$$

$$r^2 = \frac{kq_1q_2}{F}$$

$$r = \pm\sqrt{\frac{kq_1q_2}{F}}$$

Only the positive root is chosen to represent the distance in this situation

$$r = \sqrt{\frac{\left(9.0 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)(8.0 \times 10^{-6}\ \text{C})(5.0 \times 10^{-6}\ \text{C})}{5.0 \times 10^{-1}\ \text{N}}}$$

$$r = 0.84853\ \text{m}$$

$$r \cong 0.85\ \text{m}$$

(a) Since the force is attractive, the second charge must be positive.

(b) The distance between the centres of the charges is 0.85 m.

continued ►